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Impact of wind direction on near-road pollutant concentrations

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HIGHLIGHTS

- Wind direction plays significant role in variation of near road concentrations.
- Interpretation of concentration variation requires dispersion model.
- Dispersion models are useful in planning field studies.

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ABSTRACT

Exposure to roadway emissions is an emerging area of research because of recent epidemiological studies reporting association between living within a few hundred meters of high-traffic roadways and adverse health effects. The air quality impact of roadway emissions has been studied in a number of field experiments, most of which have not fully considered the impact of wind direction on near-road concentrations. This paper examines the role of wind direction by using a dispersion model to analyze data from three field studies that include measurements under varying wind directions: 1) a tracer study conducted adjacent to highway 99 in Sacramento, CA in 1981–82, 2) a field study next to a highway in Raleigh, North Carolina in 2006, and 3) a field study conducted next to a depressed highway in Las Vegas, Nevada in 2010. We find that wind direction is an important variable in characterizing exposure to roadway emissions. Under stable conditions, the near-surface concentrations at receptors up to 100 m from the road increase with wind angle before dropping off at angles close to parallel to the road. It is only for pollutants with short life times does the maximum concentration occur when the wind direction is normal to the road. We also show that current dispersion models are reliable tools for interpreting observations and for formulating plans for field studies.

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1. Introduction

The impact of roadway emissions on air quality has become prominent in light of a number of recent epidemiological studies reporting associations between population living in a close proximity to high-traffic roadways and adverse health effects (summarized in HEI, 2010). Numerous air quality monitoring studies conducted near major roadways have measured elevated concentrations, compared with overall urban background levels, of a number of air pollutants emitted by motor vehicles. Several field studies (Baldauf et al., 2008 for example) and measurement programs have been conducted to understand the relationship between near road pollutant concentrations and governing variables such as meteorology and emissions. Most of these studies have focused on wind directions close to normal to the road based on the assumption that the maximum impact of roads occurs under these conditions. Only a small number of studies have examined the impact of wind direction on concentrations and concentration gradients. Barzyk et al. (2009) found that using an effective distance to a receptor based on wind direction relative to the road provided a better explanation of concentration gradients than perpendicular distances. Kozawa et al. (2012) found that size distributions, number concentrations, and spatial gradients of ultrafine particles were significantly different for near perpendicular and parallel wind directions.

In this paper, we examine the impact of the wind direction on dispersion of pollutants near roadways by analyzing the data from a tracer study and two field studies. We also illustrate the expected behavior of concentrations with wind direction using a dispersion

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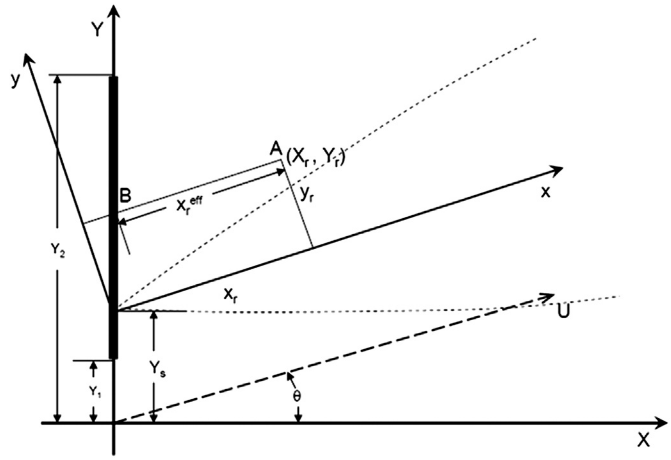

Fig. 1. Co-ordinate systems to calculate contribution of point source at Y_s to concentration at (X_r, Y_r). Note: The system *x-y* has the *x*-axis along the mean wind direction, which is at an angle to the fixed *X* axis. The dotted lines represent the plume originating from an elemental point source at (0, Y_s).

model. The analysis presented here is conducted in two steps. We first establish the validity of a roadway dispersion model by evaluating it with data from the field studies. We then use the model to conduct sensitivity studies to demonstrate the impact of wind direction on near-road concentrations of roadway pollutants.

2. Line source dispersion model

The road is represented as a set of line sources located at the center of each lane of the road. Each line source is modeled as a set of elemental point sources, as shown in Fig. 1. The contribution of the elemental point source, dC, located at (0, Y_s), to the concentration at (X_r, Y_r, Z_r) is given by the Gaussian plume formulation,

$$dC = \frac{qdY_s}{2\pi U\sigma_y(X_r)\sigma_z(X_r)}\exp\left(-\frac{Y_r^2}{2\sigma_y^2(Y_r)}\right)F(Z_r), \tag{1}$$

where $F(Z_r)$ is the vertical distribution function given by

$$F(Z_r) = \exp\left(-\frac{(h_s-Z_r)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(h_s+Z_r)^2}{2\sigma_z^2}\right), \tag{2}$$

where σ_y and σ_z are the horizontal and vertical plume spreads, which are functions of X_r, the receptor's downwind distance in the co-ordinate system aligned with the wind direction, as shown in Fig. 1. We assume that the pollutant does not undergo dry deposition, which implies that the concentration gradient is zero at the ground. The second term on the right hand side of Equation (2) imposes this condition.

The vertical spread of the plume, σ_z, from each point source is described by equations used in AERMOD (Cimorelli et al., 2005), which is representative of the current generation of dispersion models:

$$\begin{aligned}\sigma_z &= \sqrt{\tfrac{2}{\pi}}\,\tfrac{u_*X_r}{U}\left(1+0.7\tfrac{X_r}{L}\right)^{-1/3} \qquad L>0.0\\ \sigma_z &= \sqrt{\tfrac{2}{\pi}}\,\tfrac{u_*X_r}{U}\left(1+0.006\left(\tfrac{X_r}{|L|}\right)^2\right)^{1/2} \qquad L<0.0,\end{aligned} \tag{3}$$

where L is the Monin–Obukhov length defined by $L = -T_0u_*^3/(\kappa gQ_0)$, where Q_0 is the surface kinematic heat flux, u_* is the surface friction velocity, g is the acceleration due to gravity, T_0 is a reference temperature, and κ is the Von Karman constant taken to be 0.40. Equation (3) is a semi-empirical formulation (Venkatram, 1992) based on eddy diffusivity and wind speed profiles derived from Monin–Obukhov (MO) Similarity Theory (Businger et al., 1971).

The horizontal spread of the plume is based on that in AERMOD (Cimorelli et al., 2005):

$$\sigma_y = \tfrac{\sigma_vX_r}{U}(1+78X)^{-0.3}$$

where (4)

$$X = \tfrac{\sigma_vX_r}{Uz_i}$$

Here σ_v is the standard deviation of the crosswind velocity fluctuations, and z_i is the mixed layer height.

The contribution of a line source to the concentrations at a receptor (X_r, Y_r) is given by the integral of the contributions the point sources along the line,

$$C_p(X_r,Y_r) = \int_{Y_1}^{Y_1+L} dC. \tag{5}$$

We use an analytical approximation to the integral, given by Venkatram and Horst (2006),

$$C_p(X_r,Y_r)\approx\frac{qF(Z_r)}{\sqrt{2\pi}U\sigma_z\left(x_r^{eff}\right)\cos\theta}[erf(t_1)-erf(t_2)]. \tag{6}$$

where

$$x_r^{eff} = X_r/\cos\theta, \tag{7}$$

$$t_i = \frac{(Y_r-Y_i)\cos\theta - X_r\sin\theta}{\sqrt{2}\sigma_y(x_i)}, \tag{8}$$

where q is the emission rate per unit length of the line source. Here σ_y is evaluated at $X_i \equiv X_r(Y_s = Y_i)$. The definitions of t_1 and t_2 correspond to downwind distances, X_r, from the end points Y_1 and Y_2 of the line to the receptor at (X_r, Y_r). We see from Fig. 1 that the vertical spread in Equation (6) is evaluated at a downwind distance from the line source along the wind direction.

The approximation of Equation (6) breaks down at $\theta = 90°$ because of the term $\cos\theta$ in the denominator. We avoid the problem by taking the limit of $\sigma_z(X_r/\cos\theta)\cos\theta$ as θ approaches 90° to be $\sigma_z(X_r)$. This limit is consistent with the exact solution of the integral for a parallel wind when the vertical and horizontal plume spreads are linear with downwind distance. We account for this limit by modifying the denominator in the equation to $(\sigma_z(X_r)+\sigma_z(X_r/\cos\theta)\cos\theta)/2$. Comparison with the numerical solution indicates that this approach has an error of less than 25% when θ approaches 90°.

Under low wind speeds, horizontal meandering of the wind spreads the plume over large azimuth angles, which leads to concentrations at receptors upwind relative to the vector averaged wind direction. AERMOD (Cimorelli et al., 2005), and other currently used regulatory models (e.g. ADMS, Atmospheric Dispersion Modeling System, Carruthers et al., 1994), attempt to treat this situation by assuming that when the mean wind speed is close to zero, the horizontal plume spread covers 360°. If the release spreads radially in all horizontal directions, the concentration from a point source with an emission rate, Q, is given by:

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